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U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Interpolation Formulas for Viscosity of Six Gases: Air, Nitrogen, Carbon Dioxide, Helium, Argon, and Oxygen

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Interpolation Formulas for Viscosity of Six Gases: Air, Nitrogen, Carbon Dioxide, Helium, Argon, and Oxygen

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INTERPOLATION FORMULAS FOR VISCOSITY OF SIX GASES: AIR, NITROGEN, CARBON DIOXIDE, HELIUM, ARGON, AND OXYGEN

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Equations for the calculation of viscosity for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen have been developed as interpolation formulas fitted to experimental data. The approximate ranges of strict application of the equations are the ranges of temperature (20°C $\leq$ t $\leq$ 50°C) and pressure (0.04 $\leq$ p $\leq$ 4 MPa; 0.4 $\leq$ p $\leq$ 40 atm) for the experimental data. The estimates of relative residual standard deviation for the fits (0.05% for air, 0.03% for nitrogen, 0.02% for carbon dioxide, 0.02% for helium, 0.03% for argon, and 0.03% for oxygen) are in close agreement with estimates of precision for the experimental data.

Key words: Air; argon; calculation; carbon dioxide; helium; nitrogen; oxygen; viscosity.

1. INTRODUCTION

In the calibration and use of flow metering devices the precise, accurate value of the viscosity of the gas being metered is often required. The availability of simple equations relating viscosity, μ, to temperature, t, and pressure, p, would be a convenience to the engineer in calculating μ. In the present work, simple interpolation formulas have been developed which enable the engineer to conveniently make precise, accurate calculations of μ for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen using small readily available hand-held calculators. The formulas are fitted to experimental data. The data were selected from the literature on the basis of claimed accuracy and precision, and of internal consistency. The last of these criteria is particularly important for the development of empirical equations for volume flow with a dominant term of the Poiseuille form, the subject of a later paper. The sets of data published by Kestin and

his collaborators [1-10] meet these criteria and have been used to develop the formulas.

2. EXPERIMENTAL DATA

The ranges of temperature and pressure of interest in the present work are $0°C \leq t \leq 50°C$ and $0 < p \leq 4$ MPa ($0 < p \leq 40$ atm). The experimental data used in developing the equations for μ are listed in Tables 1-6. In Table 1 for dry air, the data in the first and third groups are taken from Table III of [1]; the second and fourth groups are taken from Table II of [2]; and the 50.00°C point is inferred from the data in [2]. In Table 2 for nitrogen, the first and third groups are taken from Table XI of [1]; the second, fifth, and sixth groups are taken from Table VIII of [2]; the fourth group is taken from Table III of [3]; the 20.58°C point is taken from Table XI of [1]; and the 24.920°C point is taken from Table III of [3]. In Table 3 for carbon dioxide, the 20.00°C data are taken from Table V of [1]; the second group is taken from Table IV of [2]; and the 25.00°C point is taken from Table III of [4]. In Table 4 for helium, the first group is taken from Table VII of [1]; the 25.00°C point is taken from Table IV of [5]; and the third group is taken from Table V of [2]. In Table 5 for argon, the first and second groups are taken from Table IV of [1]; the third group is taken from Table IV of [3]; and the fourth group is taken from Table III of [2]. In Table 6 for oxygen, the first and second groups are adjusted values from Table XII of [1]; the third group is taken from Table V of [10].

3. DEVELOPMENT OF EQUATIONS

The equations for μ (t,p) were developed using a procedure [6] in which $\mu(t,p)$ is expressed as

$$\mu(t,p) = \mu_o (t,0) + \Delta\mu(p). \quad (1)$$

where μ_o (t,0) is the viscosity at "zero pressure" and $\Delta\mu(p)$ is the experimental value of viscosity, $\mu_{meas.}$, minus μ_o (t,0). The procedure will be outlined below.

<u>Air</u>

The data pairs, (20.00°C, 181.94 μg/cm·s), (23.44°C, 183.75 μg/cm·s), (23.90°C, 184.21 μg/cm·s), (25.00°C, 184.62 μg/cm·s), and (50.00°C, 197.31 μg/cm·s), taken from Table 1, were fitted by least squares to an equation quadratic in t to enable calculation of μ at 0.101325 MPa, μ_1. The small departures of p from this value of pressure for these pairs are not significant. The resulting equation is

$$\mu_1 = 170.368 + 0.605434\ t - 1.33200 \times 10^{-3}\ t^2, \quad (2)$$

where μ_1 is in μg/cm·s and t is in °C. To reduce μ_1 to "zero pressure," μ_o, the value of the increase in μ per 0.10325 MPa, 0.11 μg/cm·s, estimated from the tabulated data was subtracted from μ_1 resulting in

$$\mu_o = 170.258 + 0.605434\ t - 1.33200 \times 10^{-3}\ t^2. \quad (3)$$

Calculated values of μ_o are listed in Table 1.

The difference, $\Delta\mu$, between the experimental values of μ and calculated values of μ_o is also listed in Table 1. The values of $\Delta\mu$ were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta\mu = -2.44358 \times 10^{-3} + 1.17237\ p + 0.125541\ p^2. \qquad (4)$$

Equations (3) and (4) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = \mu_o + \Delta\mu = 170.256 + 0.605434\ t - 1.33200 \times 10^{-3}\ t^2$$

$$+ 1.17237\ p + 0.125639\ p^2, \qquad (5)$$

where $\mu_{calc.}$ is in <u>μg/cm·s</u>, t is in <u>°C</u>, and p is in <u>MPa</u>. Values of $\mu_{calc.}$ and differences between $\mu_{calc.}$ and experimental values, $\mu_{meas.}$, are listed in Table 1.

The estimate of residual standard deviation (RSD), that is, the estimate of the standard deviation of $\mu_{calc.}-\mu_{meas.}$, is 0.10 μg/cm·s for the 19 differences (n=19). The estimate of the relative residual standard deviation (RRSD), that is, the ratio of RSD to the mean $\mu_{meas.}$, is 0.05%. Kestin and Leidenfrost [1] estimated that for their measurements "a precision ranging from ±0.01% to ±0.07%, depending on the gas, has been achieved. The final accuracy of the measurements is estimated to be of the order of ±0.05%." DiPippo and Kestin [2] estimated the precision of their data to be ±0.05%; they reached the conclusion that "no meaningful assessment of the <u>accuracy</u> of the present data can be given if by accuracy we mean the <u>irreducible</u> discrepancy between the best measurements available at any particular time."

For μ in μPa·s, t in °C, and p in MPa, equation (5) becomes

$$\mu_{calc.} = 17.0256 + 6.05434 \times 10^{-2}\ t - 1.33200 \times 10^{-4}\ t^2 + 0.117237\ p + 1.25639 \times 10^{-2}\ p^2. \quad (6)$$

For μ in 10^{-6} lb ft^{-1} sec^{-1}, t in °C, and p in PSI, equation (5) becomes

$$\mu_{calc.} = 11.4407 + 4.06833 \times 10^{-2}\ t - 8.95063 \times 10^{-5}\ t^2 + 5.43165 \times 10^{-4}\ p + 4.01338 \times 10^{-7}\ p^2. \quad (7)$$

Nitrogen

The data pairs, (20.58°C, 175.93 μg/cm·s), (21.98°C, 176.56 μg/cm·s), (23.15°C, 177.05 μg/cm·s), (24.920°C, 177.94 μg/cm·s), (29.75°C, 180.08 μg/cm·s), and (49.37°C, 189.71 μg/cm·s), taken from Table 2, were fitted by least squares to an equation quadratic in t to enable calculation of μ_1. The resulting equation is

$$\mu_1 = 167.335 + 0.392728\ t + 1.22474 \times 10^{-3}\ t^2. \quad (8)$$

To reduce μ_1 to μ_o, 0.11 μg/cm·s estimated from the tabulated data was subtracted from μ_1 resulting in

$$\mu_o = 167.225 + 0.392728\ t + 1.22474 \times 10^{-3}\ t^2. \quad (9)$$

The values of $\Delta\mu$ were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta\mu = -1.12860 \times 10^{-2} + 1.24165\ p + 9.87206 \times 10^{-2}\ p^2. \qquad (10)$$

Equations (9) and (10) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = 167.214 + 0.392728\ t + 1.22474 \times 10^{-3}\ t^2$$

$$+ 1.24165\ p + 9.87206 \times 10^{-2}\ p^2, \qquad (11)$$

where $\mu_{calc.}$ is in <u>μg/cm·s</u>, t is in <u>°C</u>, and p is in <u>MPa</u>.

The RSD is 0.05 μg/cm·s for n = 50; the RRSD is 0.03%. Kestin et. al. [3] estimated the accuracy of their experimental measurements to be of the order of $\pm$0.2% and the relative precision to be 0.03%. The accuracy and precision estimates quoted above for air from [1] and [2] apply also to nitrogen.

For μ in <u>μPa·s</u>, t in <u>°C</u>, and p in <u>MPa</u>, equation (11) becomes

$$\mu_{calc.} = 16.7214 + 3.92728 \times 10^{-2}\ t + 1.22474 \times 10^{-4}\ t^2$$

$$+ 0.124165\ p + 9.87206 \times 10^{-3}\ p^2. \qquad (12)$$

For μ in <u>10^{-6} lb ft^{-1} sec^{-1}</u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (11) becomes

$$\mu_{calc.} = 11.2363 + 2.63901 \times 10^{-2}\ t + 8.22987 \times 10^{-5}\ t^2$$

$$+ 5.75263 \times 10^{-4}\ p + 3.15351 \times 10^{-7}\ p^2. \qquad (13)$$

Carbon Dioxide

The data pairs, (20.00°C, 146.63 μg/cm·s), (25.00°C, 149.09 μg/cm·s), (30.40°C, 151.81 μg/cm·s), and (49.12°C, 161.75 μg/cm·s), taken from Table 3, were fitted by least squares to an equation quadratic in t to enable calculation of μ_1. The resulting equation is

$$\mu_1 = 137.335 + 0.441133\ t + 1.12987 \times 10^{-3}\ t^2. \qquad (14)$$

To reduce μ_1 to μ_o, 0.13 μg/cm·s estimated from the tabulated data was subtracted from μ_1 resulting in

$$\mu_o = 137.205 + 0.441133\ t + 1.12987 \times 10^{-3}\ t^2. \qquad (15)$$

The values of $\Delta\mu$ were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta\mu = 0.133827 + 6.28105 \times 10^{-2}\ p + 0.562974\ p^2. \qquad (16)$$

Equations (15) and (16) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = 137.339 + 0.441133\ t + 1.12987 \times 10^{-3}\ t^2 + 6.28105 \times 10^{-2}\ p + 0.562974\ p^2, \qquad (17)$$

where $\mu_{calc.}$ is in <u>μg/cm·s</u>, t is in <u>°C</u>, and p is in <u>MPa</u>.

The RSD is 0.04 μg/cm·s for n = 11; the RRSD is 0.02%. Kestin et. al. [4] estimated the accuracy of the 25.00°C point, "expressed as the maximum

estimated uncertainty in the quoted values," to be ±0.1%. The accuracy and precision estimates quoted above for air from [1] and [2] apply also to carbon dioxide.

For μ in <u>μPa·s</u>, t in <u>°C</u>, and p in <u>MPa</u>, equation (17) becomes

$$\mu_{calc.} = 13.7339 + 4.41133 \times 10^{-2}\ t + 1.12987 \times 10^{-4}\ t^2$$

$$+ 6.28105 \times 10^{-3}\ p + 5.62974 \times 10^{-2}\ p^2. \qquad (18)$$

For μ in <u>10^{-6} lb ft^{-1} sec^{-1}</u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (17) becomes

$$\mu_{calc.} = 9.22876 + 2.96428 \times 10^{-2}\ t + 7.59238 \times 10^{-5}\ t^2$$

$$+ 2.91005 \times 10^{-5}\ p + 1.79836 \times 10^{-6}\ p^2. \qquad (19)$$

<u>Helium</u>

The data pairs, (20.00°C, 196.14 μg/cm·s), (24.28°C, 198.19 μg/cm·s), (25.00°C, 198.59 μg/cm·s), (30.56°C, 201.18 μg/cm·s), and (52.79°C, 211.04 μg/cm·s), were fitted by least squares to an equation quadratic in t to enable calculation of μ_1. The effect of pressure on μ for helium is so small that no correction is made to reduce μ_1 to μ_o. The resulting equation is

$$\mu_1 = \mu_o = 185.946 + 0.530773\ t - 1.04982 \times 10^{-3}\ t^2. \qquad (20)$$

The values of $\Delta\mu$ were fitted by least squares to an equation linear in p. The resulting equation is

$$\Delta\mu = 2.91664 \times 10^{-2} - 6.99813 \times 10^{-2}\ p. \qquad (21)$$

Equations (20) and (21) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = 185.975 + 0.530773\ t - 1.04982 \times 10^{-3}\ t^2 - 6.99813 \times 10^{-2}\ p, \qquad (22)$$

where $\mu_{calc.}$ is in <u>μg/cm·s</u>, t is in <u>°C</u>, and p is in <u>MPa</u>.

The RSD is 0.04 μg/cm·s for n = 15; the RRSD is 0.02%. The accuracy and precision estimates quoted above for air from [1] and [2] apply also to helium. The 25.00°C °C value is estimated to be accurate within ± 0.1% [5].

For μ in <u>μPa·s</u>, t in <u>°C</u>, and p in <u>MPa</u>, equation (22) becomes

$$\mu_{calc.} = 18.5975 + 5.30773 \times 10^{-2}\ t - 1.04982 \times 10^{-4}\ t^2 - 6.99813 \times 10^{-3}\ p. \qquad (23)$$

For μ in <u>10^{-6} lb ft^{-1} sec^{-1}</u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (22) becomes

$$\mu_{calc.} = 12.4969 + 3.56663 \times 10^{-2}\ t - 7.05446 \times 10^{-5}\ t^2 - 3.24228 \times 10^{-5}\ p. \qquad (24)$$

<u>Argon</u>

The data pairs, (20.00°C, 222.86 μg/cm·s), (24.39°C, 225.79 μg/cm·s), (25.00°C, 226.36 μg/cm·s), and (50.31°C, 243.43 μg/cm·s), taken from Table 5, were fitted by least squares to an equation quadratic in t to enable calculation of μ_1. The resulting equation is

$$\mu_1 = 208.940 \div 0.702190\ t - 3.30712 \times 10^{-4}\ t^2. \qquad (25)$$

To reduce μ_1 to μ_o, 0.21 μg/cm·s estimated from the tabulated data was subtracted from μ_1 resulting in

$$\mu_o = 208.730 + 0.702190\ t - 3.30712 \times 10^{-4}\ t^2. \qquad (26)$$

The values of $\Delta\mu$ were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta\mu = 3.17420 \times 10^{-2} + 1.73987\ p + 0.152358\ p^2. \qquad (27)$$

Equations (26) and (27) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = 208.762 + 0.702190\ t - 3.30712 \times 10^{-4}\ t^2$$

$$+ 1.73987\ p + 0.152358\ p^2, \qquad (28)$$

where $\mu_{calc.}$ is in <u>μg/cm·s</u>, t is in <u>°C</u>, and p is in <u>MPa</u>.

The RSD is 0.07 μg/cm·s for n = 38; the RRSD is 0.03%. The estimates of accuracy and precision of the experimental data for argon are those quoted above from [1], [2], and [3].

For μ in <u>μPa·s</u>, t in <u>°C</u>, and p in <u>MPa</u>, equation (28) becomes

$$\mu_{calc.} = 20.8762 + 7.02190 \times 10^{-2}\ t - 3.30712 \times 10^{-5}\ t^2$$

$$+ 0.173987\ p + 1.52358 \times 10^{-2}\ p^2. \qquad (29)$$

$$\mu_{calc.} = 14.0282 + 4.71850 \times 10^{-2}\ t - 2.22228 \times 10^{-5}\ t^2 + 8.06091 \times 10^{-4}\ p + 4.86689 \times 10^{-7}\ p^2. \qquad (30)$$

Oxygen

The data pairs, (20.00°C, 203.17 μg/cm·s), (25.00°C, 206.25 μg/cm·s), (35.00°C, 212.18 μg/cm·s), and (50.00°C, 220.80 μg/cm·s), taken from Table 6, were fitted by least squares to an equation quadratic in t to enable calculation of μ_1. The resulting equation is

$$\mu_1 = 190.539 + 0.650043\ t - 8.97542 \times 10^{-4}\ t^2. \qquad (31)$$

To reduce μ_1 to μ_o, 0.12 μg/cm·s estimated from the tabulated data was subtracted from μ_1 resulting in

$$\mu_o = 190.419 + 0.650043\ t - 8.97542 \times 10^{-4}\ t^2. \qquad (32)$$

The values of $\Delta\mu$ were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta\mu = -0.0239595 + 0.130897\ p + 1.323418 \times 10^{-3}\ p^2. \qquad (33)$$

Equations (32) and (33) were added together to synthesize the final equation for calculating μ:

$$\mu_{calc.} = 190.395 + 0.650043\ t - 8.97542 \times 10^{-4}\ t^2 + 0.130897\ p + 1.32418 \times 10^{-3}\ p^2 \qquad (34)$$

where $\mu_{calc.}$ is in $\mu g/cm \cdot s$, t is in °C, and p is in atm.

The RSD is 0.06 g/cm s for n = 16; the RRSD is 0.03%. The estimates of accuracy and precision of the experimental data for oxygen are those quoted above from [1], [2], and [3].

For μ in $\mu Pa \cdot s$, t in °C, and p in MPa, equation (34) becomes

$$\mu_{calc.} = 19.0395 + 6.50043 \times 10^{-2}\ t - 8.97542 \times 10^{-5}\ t^2 + 0.129185\ p + 1.28975 \times 10^{-2}\ p^2. \qquad (35)$$

For μ in 10^{-6} lb ft^{-1} sec^{-1}, t in °C, and p in PSI, equation (34) becomes

$${}_{calc.} = 12.7940 + 4.36809 \times 10^{-2}\ t - 6.03121 \times 10^{-5}\ t^2 + 5.98525 \times 10^{-4}\ p + 4.11587 \times 10^{-7}\ p^2. \qquad (36)$$

4. RANGES OF APPLICATION OF THE EQUATIONS

The equations developed in this paper are interpolation formulas fitted to experimental data. The range of strict application is indicated by the range of t and p of the experimental data listed in Tables 1-5. In the absence of measurements of μ for temperatures below 20°C of comparable quality to that of the data in the tables, there are two options in extending calculations below 20°C ($0 < t < 20$°C): 1) apply the extended law of corresponding states [3,7-10]; 2) extrapolate using the equations developed here, with probable loss in accuracy. Either option might be followed until suitable experimental data at temperatures below 20°C became available.

Hanley et al. [11] have developed a functional form to represent critically evaluated viscosity and thermal conductivity coefficient data, and have generated tables. The gases treated by Hanley et al. include nitrogen and argon. Values of μ calculated using the formulas in the present work have been compared with interpolated values from the tables in [11] at 0°C, 5°C, 10°C, 15°C, 20°C, and 25°C, and 0.1 MPa, for nitrogen and argon. The deviation of the values in the present work from the values from reference [11], expressed in percent are: for nitrogen, +0.26% at 0°C, +0.02% at 5°C, -0.12% at 10°C, -0.28% at 15°C, -0.32% at 20°C, and -0.38% at 25°C; for argon, -1.16% at 0°C, -1.10% at 5°C, -0.99% at 10°C, -0.86% at 15°C, -0.78% at 20°C, and -0.66% at 25°C. These deviations are all well within the uncertainty, $\pm$ 2%, estimated by Hanley et al. for their tables.

5. CONCLUSIONS

Equations (interpolation formulas fitted to experimental data) for the calculation of μ for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen have been developed. The estimates of relative residual standard deviation for the fits are in close agreement with the estimates of precision for the experimental data in the above stated ranges.

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Nomenclature

p = pressure

RRSD = estimate of relative residual standard deviation

RSD = estimate of residual standard deviation

t = temperature in °C

$\Delta\mu = \mu_{meas.} - \mu_o$

μ = viscosity

$\mu_{calc.}$ = calculated value of viscosity

$\mu_{meas.}$ = experimental value of viscosity

μ_o = viscosity at "zero pressure"

μ_1 = viscosity at 0.101325 MPa

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Table 1

Viscosity of Dry Air

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
20.00	1.00	181.94	181.83	0.11	181.95	+0.01
20.00	4.39	182.38	181.83	0.55	182.37	-0.01
20.00	7.79	182.84	181.83	1.01	182.83	-0.01
20.00	11.22	183.32	181.83	1.49	183.32	0.00
20.00	14.61	183.88	181.83	2.05	183.84	-0.04
20.00	18.03	184.40	181.83	2.67	184.39	-0.01
20.00	21.40	184.98	181.83	3.15	184.96	-0.02
20.00	34.97	187.70	181.83	5.87	187.56	-0.14
23.44	1.07	183.75	183.72	0.03	183.85	+0.10
24.68	0.69	184.45	184.39	0.06	184.47	+0.02
24.00	1.71	184.33	184.02	0.31	184.22	-0.11
23.90	1.04	184.21	183.97	0.24	184.09	-0.12
23.89	0.83	184.13	183.96	0.17	184.06	-0.07
23.97	0.42	184.08	184.00	0.08	184.05	-0.03
25.00	1.00	184.62	184.56	0.06	184.68	+0.06
24.99	18.01	186.98	184.56	2.42	187.12	+0.14
24.99	35.12	190.18	184.56	5.62	190.32	+0.14
49.91	1.70	197.25	197.16	0.09	197.36	+0.11
49.39	1.08	196.99	196.91	0.08	197.04	+0.05
[a]50.00	1.00	197.31				

[a]Used for calculating μ_1 only.

Table 2

Viscosity of Nitrogen

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
20.00	34.82	181.24	175.57	5.67	181.17	-0.07
20.00	20.48	178.64	175.57	3.07	178.56	-0.08
20.00	18.04	178.14	175.57	2.57	178.16	+0.02
20.00	14.59	177.58	175.57	2.01	177.61	+0.03
20.00	11.17	176.96	175.57	1.39	177.09	+0.13
20.00	7.79	176.50	175.57	0.93	176.60	+0.10
20.00	4.38	176.06	175.57	0.49	176.13	+0.07
20.00	1.00	175.69	175.57	0.12	175.69	0.00
20.00	0.687	175.62	175.57	0.05	175.65	+0.03
20.00	0.385	175.57	175.57	0.00	175.61	+0.04
21.75	1.57	176.52	176.35	0.17	176.54	+0.02
21.98	1.06	176.56	176.45	0.11	176.57	+0.01
24.44	1.67	177.80	177.55	0.25	177.77	-0.03
24.56	1.53	177.84	177.61	0.23	177.79	-0.05
24.72	1.43	177.86	177.68	0.18	177.85	-0.01
24.84	1.32	177.86	177.74	0.12	177.90	+0.04
25.07	1.24	178.00	177.84	0.16	177.99	-0.01
25.15	1.15	177.99	177.88	0.11	178.02	+0.03
23.22	1.10	177.14	177.00	0.14	177.13	-0.01
23.15	1.04	177.05	176.97	0.08	177.08	+0.03
25.00	41.86	184.79	177.81	6.98	184.84	+0.05
25.00	28.21	182.12	177.81	4.31	182.16	+0.04
25.00	14.60	179.89	177.81	2.08	179.85	-0.04
25.00	7.80	178.83	177.81	1.02	178.84	+0.01
25.00	0.991	177.96	177.81	0.15	177.92	-0.04

Table 2 (continued)

Nitrogen

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
25.00	1.000	177.98	177.81	0.17	177.93	-0.05
25.00	1.714	178.06	177.81	0.25	178.02	-0.04
25.00	2.300	178.13	177.81	0.32	178.09	-0.04
25.00	3.009	178.19	177.81	0.38	178.19	0.00
25.00	3.715	178.32	177.81	0.51	178.28	-0.04
25.00	4.341	178.41	177.81	0.60	178.37	-0.04
25.00	4.979	178.44	177.81	0.63	178.45	+0.01
25.00	5.579	178.59	177.81	0.78	178.53	-0.06
25.00	6.613	178.73	177.81	0.92	178.68	-0.05
25.00	7.307	178.81	177.81	1.00	178.77	-0.04
25.00	8.029	178.90	177.81	1.09	178.88	-0.02
25.00	8.954	179.04	177.81	1.23	179.01	-0.03
25.00	9.931	179.17	177.81	1.36	179.15	-0.02
25.00	12.567	179.59	177.81	1.78	179.54	-0.05
25.00	14.880	179.88	177.81	2.07	179.90	+0.02
25.00	20.051	180.66	177.81	2.85	180.73	+0.07
25.00	24.644	181.45	177.81	3.64	181.52	+0.07
25.00	29.838	182.49	177.81	4.68	182.46	-0.03
25.00	34.816	183.45	177.81	5.64	183.41	-0.04
25.00	39.919	184.43	177.81	6.62	184.44	+0.01
29.75	1.06	180.08	179.99	0.09	180.11	+0.03
29.93	1.06	180.12	180.08	0.04	180.20	+0.08
49.80	1.64	189.98	189.82	0.16	190.02	+0.04
49.73	1.64	190.01	189.78	0.23	189.98	-0.03
49.37	1.06	189.71	189.60	0.11	189.72	+0.01
[a]20.58	1.00	175.93				
[a]24.920	1.00	177.94				

[a]Used for calculating μ_1 only.

Table 3

Viscosity of Carbon Dioxide

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
20.00	18.02	148.62	146.48	2.14	148.61	-0.01
20.00	14.63	147.93	146.48	1.45	147.94	+0.01
20.00	11.18	147.39	146.48	0.91	147.41	+0.02
20.00	7.78	147.01	146.48	0.53	147.01	0.00
20.00	4.38	146.78	146.48	0.30	146.75	-0.03
20.00	0.976	146.63	146.48	0.15	146.63	0.00
20.00	0.640	146.56	146.48	0.08	146.62	+0.06
30.34	1.69	151.83	151.63	0.20	151.79	-0.04
30.40	1.06	151.81	151.66	0.15	151.81	0.00
49.12	1.08	161.75	161.60	0.15	161.75	0.00
25.00	1.00	149.09	148.94	0.15	149.09	0.00

Table 4

Viscosity of Helium

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
20.00	34.85	195.94	196.14	-0.20	195.92	-0.02
20.00	21.40	195.99	196.14	-0.15	196.02	+0.03
20.00	18.00	196.02	196.14	-0.12	196.04	+0.02
20.00	14.61	196.09	196.14	-0.05	196.07	-0.02
20.00	11.19	196.03	196.14	-0.11	196.09	+0.06
20.00	7.80	196.17	196.14	+0.03	196.11	-0.06
20.00	4.39	196.19	196.14	+0.05	196.14	-0.05
20.00	1.01	196.14	196.14	0.00	196.16	+0.02
25.00	1.0	198.59	198.56	+0.03	198.58	-0.01
24.01	1.57	198.12	198.08	+0.04	198.10	-0.02
24.28	1.06	198.19	198.21	-0.02	198.23	+0.04
30.49	1.71	201.20	201.15	+0.05	201.17	-0.03
30.56	1.07	201.18	201.19	-0.01	201.21	+0.03
53.00	1.61	211.16	211.13	+0.03	211.15	-0.01
52.79	1.07	211.04	211.04	0.00	211.06	+0.02

Table 5

Viscosity of Argon

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
20.00	30.81	229.66	222.64	+7.02	229.59	-0.07
20.00	21.42	227.16	222.64	+4.52	227.17	+0.01
20.00	18.06	226.41	222.64	+3.77	226.37	-0.04
20.00	14.63	225.58	222.64	+2.94	225.59	+0.01
20.00	11.22	224.86	222.64	+2.22	224.85	-0.01
20.00	7.79	224.18	222.64	+1.54	224.14	-0.04
20.00	4.37	223.50	222.64	+0.86	223.47	-0.03
20.00	1.00	222.86	222.64	+0.22	222.85	-0.01
20.00	0.709	222.81	222.64	+0.17	222.80	-0.01
20.00	0.384	222.73	222.64	+0.09	222.74	+0.01
25.00	27.91	232.21	226.08	+6.13	232.23	+0.02
25.00	21.41	230.42	226.08	+4.34	230.60	+0.18
25.00	14.61	228.96	226.08	+2.88	229.02	+0.06
25.00	7.81	227.57	226.08	+1.49	227.58	+0.01
25.00	1.00	226.38	226.08	+0.30	226.29	-0.09
25.00	1.000	226.34	226.08	+0.26	226.29	-0.05
25.00	2.041	226.45	226.08	+0.37	226.48	+0.03
25.00	3.034	226.70	226.08	+0.62	226.66	-0.04
25.00	4.048	226.82	226.08	+0.74	226.85	+0.03
25.00	5.110	227.13	226.08	+1.05	227.05	-0.08
25.00	6.035	227.25	226.08	+1.17	227.23	-0.02
25.00	7.158	227.49	226.08	+1.41	227.45	-0.04
25.00	8.586	227.75	226.08	+1.67	227.74	-0.01
25.00	10.029	228.12	226.08	+2.04	228.04	-0.08
25.00	12.403	228.59	226.08	+2.51	228.54	-0.05
25.00	15.288	229.13	226.08	+3.05	229.17	+0.04
25.00	20.266	230.33	226.08	+4.25	230.33	0.00
25.00	22.637	230.94	226.08	+4.86	230.90	-0.04
25.00	24.542	231.36	226.08	+5.28	231.38	+0.02
25.00	29.985	232.83	226.08	+6.75	232.80	-0.03
25.00	35.156	234.26	226.08	+8.18	234.24	-0.02
25.00	40.191	235.71	226.08	+9.63	235.72	+0.01

Table 5 (continued)

Argon

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm·s)
24.33	1.56	225.83	225.62	+0.21	225.93	+0.10
24.39	1.07	225.79	225.66	+0.13	225.88	+0.09
49.37	1.73	242.68	242.59	+0.09	242.93	-0.25
49.43	1.46	243.05	242.63	+0.42	242.92	-0.13
49.83	1.22	243.17	242.90	+0.27	243.15	-0.02
50.31	1.08	243.43	243.22	+0.21	243.44	+0.01

Table 6
Viscosity of Oxygen

Temp., t, (C)	Press., P, (atm)	$\mu_{meas.}$ (μg/cm·s)	μ_o (μg/cm·s)	$\Delta\mu$ (μg/cm·s)	$\mu_{calc.}$ (μg/cm·s)	$\mu_{calc.}-\mu_{meas.}$ (μg/cm.s)
20.00	21.40	206.57	203.06	3.51	206.44	-0.13
20.00	18.02	205.86	203.06	2.80	205.82	-0.04
20.00	14.58	205.19	203.06	2.13	205.23	+0.04
20.00	11.19	204.70	203.06	1.64	204.67	-0.03
20.00	7.77	204.12	203.06	1.06	204.13	+0.01
20.00	4.39	203.61	203.06	0.55	203.64	+0.03
20.00	0.981	203.17	203.06	0.11	203.17	0
20.00	0.634	203.13	203.06	0.07	203.12	-0.01
25.00	41.83	213.87	206.11	7.76	213.88	+0.01
25.00	28.22	210.79	206.11	4.68	210.83	+0.04
25.00	14.61	208.25	206.11	2.14	208.28	+0.03
25.00	7.80	207.06	206.11	0.95	207.19	+0.13
25.00	0.998	206.25	206.11	0.14	206.22	-0.03
25.00	1	206.25	206.11	0.14	206.22	-0.03
35.00	1	212.18	212.07	0.11	212.18	0
50.00	1	220.80	220.68	0.12	220.79	-0.01

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Frank E. Jones

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Equations for the calculation of viscosity for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen have been developed as interpolation formulas fitted to experimental data. The approximate ranges of strict application of the equations are the ranges of temperature ($20°C \leq t \leq 50°C$) and pressure ($0.04 \leq p \leq 4$ MPa; $0.4 \leq p \leq 40$ atm) for the experimental data. The estimates of relative residual standard deviation for the fits (0.05% for air, 0.03% for nitrogen, 0.02% for carbon dioxide, 0.02% for helium, 0.03% for argon, and 0.03% for oxygen) are in close agreement with estimates of precision for the experimental data.

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air; argon; calculation; carbon dioxide; helium; nitrogen; oxygen; viscosity

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